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Recent two-photon results at Belle

H. Nakazawa (Belle Collaboration)
National Central University (Taiwan)

Abstract. We review recent measurements of pure neutral final state production, $\gamma\gamma \to \pi^0\pi^0$ and $\eta\pi^0$, and observations of new charmoniumlike resonances, $X(3915)$ and $X(4350)$, in the two-photon processes at the Belle experiment.

1. Introduction

Two-photon production of exclusive hadronic final states provides useful information about resonances and pertubative and nonperturbative QCD. From theoretical viewpoint, two-photon process is attractive because of the absence of strong interactions in the initial state and the possibility of calculating $\gamma\gamma \to q\bar{q}$ amplitudes. In addition, the quantum numbers of the final state are restricted to states of charge conjugation $C = +1$ with $J = 1$ forbidden.

We have measured charged pion pair [1, 2, 3], charged kaon pair [3, 4], neutral kaon pair [5], proton antiproton pair [6] and D-meson pair [7] production in two-photon collisions. The statistics of these measurements is 2 to 3 orders of magnitude highter than in the pre-B-factory measurements, opening a new era in studies of two-photon physics.

In this report, we summarize measurements of neutral final state production, $\gamma\gamma \to \pi^0\pi^0$ and $\eta\pi^0$ and observations of charmoniumlike resonances $X(3915)$ and $X(4350)$.

2. Neutral Pair Production

We use the data samples of 95 fb^{-1} [8] and 223 fb^{-1} [9] for $\gamma\gamma \to \pi^0\pi^0$ and of 223 pb^{-1} for $\gamma\gamma \to \eta\pi^0$ [10] collected with the Belle detector [11] at the energy-asymmetric e^+e^- KEKB collider [12]. Our analysis is based on the "zero-tag" mode, where by collecting small total transverse momentum events, $|\sum \vec{p}_t| < 0.05\,\mathrm{GeV}/c$, the incident photons are guaranteed to have small virtuality.

2.1. Light Resonance Study

Figures 1 (left) shows the total cross section for $\gamma\gamma \to \pi^0\pi^0$ integrated over $|\cos\theta^*| < 0.8$, where θ^* is a scattering angle of one of two mesons with respect to the photon beam axis. We observe clear peaks for the $f_0(980)$ near 0.98 GeV and the $f_2(1270)$ near 1.25 GeV and find at least two more structures around 1.65 and 1.95 GeV.

We perform the partial wave analysis to the W (two-photon invariant mass) region 0.8 GeV $< W <$ 1.6 GeV and 1.7 GeV $< W <$ 2.5 GeV separately. In the lower energy region, in addition to $f_0(980)$, $f_2(1270)$ and $f_2'(1575)$ we introduce a scalar meson $f_0(Y)$ to take into account a resonance-like structure around 1.2 GeV in the $\hat{S}$ wave [8] which can be either the $f_0(1370)$ or

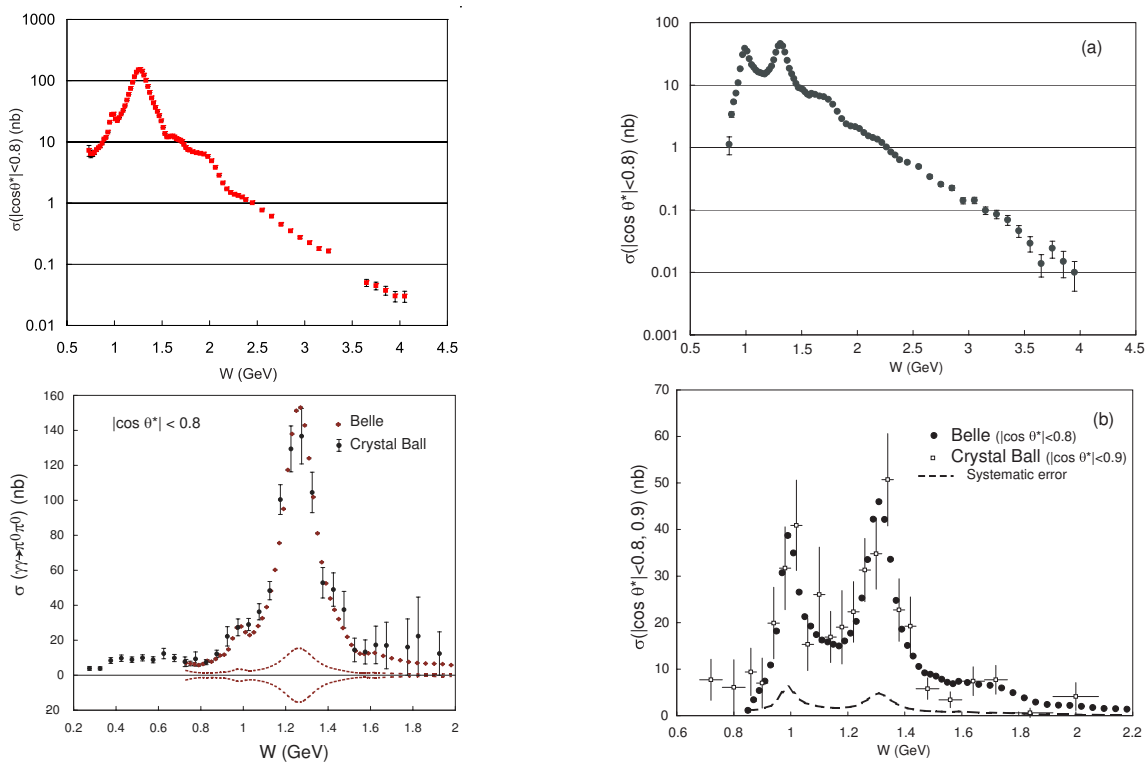

Figure 1. Left: (top) Cross section for $\gamma\gamma \to \pi^0\pi^0$ ($|\cos\theta^*| < 0.8$). Data points near 3.5 GeV are not shown because of uncertainty from the χ_{cJ} subtraction. (bottom) Comparison with the Crystal Ball measurement [13]. Dashed lines show the systematic errors for the Belle measurement. Right: Cross section for $\gamma\gamma \to \eta\pi^0$ ($|\cos\theta^*| < 0.8$) on (top) logarithmic and (bottom) linear scale compared with the Crystal Ball measurement ($|\cos\theta^*| < 0.9$) [14]. The corrections for different $|\cos\theta^*|$ coverage are not made. The dashed curve shows the size of the systematic error.

$f_0(1500)$ or a mixture of them. In the higher energy region we include $f_4(2050)$ and $f_2(1950)$. Here we denote the latter as the "$f_2(1950)$" assuming that the $f_2(1950)$ is just an empirical parameterization representing any possible resonances in this W region [15]. The resulting parameters obtained by the fit are listed in Table 1. The $M(f_4(2050))$ and "$M(f_2(1950))$" flip and the widths are about two times larger than their PDG values. Although a more sophisticated model is necessary, our data clearly require a G-wave component, and the unacceptably worse fit without the $f_4(2050)$ strongly supports its finite two-photon coupling.

Figures 1 (right) shows the cross section for $\gamma\gamma \to \eta\pi^0$ integrated over $|\cos\theta^*| < 0.8$, on logarithmic and linear scales for partial W regions. The data points are in good agreement with those from Crystal Ball [14]. We find three resonant structures: near 0.98 GeV ($a_0(980)$), 1.32 GeV ($a_2(1320)$) and 1.7 GeV (probably the $a_2(1700)$). We focus on the region, $W <$ 1.5 GeV, where $J > 2$ waves can be safely neglected, because a fit with $a_2(1320)$ parameters doesn't give a stable result. Introducing $a_0(Y)$ to model the shoulder around 1.2 GeV in the $\hat{S}^2$ [10] wave, we fit differential cross sections for the range 0.90 GeV $< W <$ 1.46 GeV. The fit result is summarized in Table 1.

	$\pi^0\pi^0$ (95/fb [8])	$\pi^0\pi^0$ (223/fb [9])	$\eta\pi^0$ (223/fb [10])
	$f_0(980)$	$f_4(2050)$	$a_0(980)$
Mass [MeV/c^2]	982.2 ± 1.0	1885^{+14}_{-13}	$982.3^{+0.6+3.1}_{-0.7-4.7}$
Γ [MeV]	$285.5^{+17.2}_{-17.1}$	453 ± 20	$75.6 \pm 1.6^{+17.4}_{-10.0}$
$\Gamma_{\gamma\gamma}(\pi^0\pi^0/\eta\pi^0)$ [eV]		$7.7^{+1.2}_{-1.1}$	123^{+3+501}_{-2-43}
	$f_0(Y)$	"$f_2(1950)$"	$a_0(Y)$
Mass [MeV/c^2]	1469.7 ± 4.7	2038^{+13}_{-11}	$1316.8^{+0.7+24.7}_{-1.0-4.6}$
Γ [MeV]	$89.7^{+8.1}_{-6.6}$	441^{+27}_{-25}	$65.0^{+2.1+99.1}_{-5.4-32.6}$
$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0/\eta\pi^0)$ [eV]	$11.2^{+5.0}_{-4.0}$	54^{+23}_{-14}	$432 \pm 6^{+1073}_{-256}$

Table 1. Fit results for the light resonances.

Process	n	W range (GeV)	$\lvert\cos\theta^*\rvert$ range	Reference
$\eta\pi^0$	$10.5 \pm 1.2 \pm 0.5$	3.1-4.1	< 0.8	[10]
$\pi^0\pi^0$	$8.0 \pm 0.5 \pm 0.4$	3.1-4.1	< 0.8	[9]
$\pi^0\pi^0$	$6.9 \pm 0.6 \pm 0.7$	3.1-4.1	< 0.6	[9]
$\pi^+\pi^-$	$7.9 \pm 0.4 \pm 1.5$	3.0-4.1	< 0.6	[3]
K^+K^-	$7.3 \pm 0.3 \pm 1.5$	3.0-4.1	< 0.6	[3]
$K^0_SK^0_S$	$10.5 \pm 0.6 \pm 0.5$	2.4-4.0	< 0.6	[5]

Table 2. Power-low dependence parameters of the cross sections $\sigma \propto W^{-n}$ in various reactions.

Process	Mass (MeV/c^2)	Width (MeV)	events	significance	Reference
$X(3915)$	$3915 \pm 3 \pm 2$	$17 \pm 10 \pm 3$	$49 \pm 14 \pm 4$	7.7σ	[19]
$X(4350)$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13.9^{+18}_{-9} \pm 4$	$8.8^{+4.2}_{-3.2}$	3.2σ	[20]

Table 3. Measured values for charmoniumlike states $X(3915)$ and $X(4350)$.

2.2. Analysis of the higher-energy region

The leading-order QCD calculation [16, 17] predicts $d\sigma(\pi^0\pi^0)/d\sigma(\pi^+\pi^-) \approx 0.07$ at $|\cos\theta^*| = 0$, changing to ≈ 0.4 at $|\cos\theta^*| = 0.6$, and $d\sigma(\eta\pi^0)/d\sigma(\pi^0\pi^0) = 0.46(f_\eta/f_{\pi^0})^2$ where $f_\eta(f_{\pi^0})$ is the $\eta(\pi^0)$ form factor, while $d\sigma(\pi^0\pi^0)/d\sigma(\pi^+\pi^-) = 0.05$ by the handbag model [18]. We can evaluate these predictions at $W > 2.4$ GeV where the contribution from resonances is small.

The power-law W^{-n} dependence parameter of the total cross section for $\gamma\gamma \to \pi^0\pi^0$ ($|\cos\theta^*| < 0.8$) is obtained to be $n = 8.0 \pm 0.5 \pm 0.4$, and the cross section ratio to $\sigma(\pi^+\pi^-)$ is found to be $0.32 \pm 0.03 \pm 0.05$ for 3.1 GeV $< W <$ 4.1 GeV. For $\gamma\gamma \to \eta\pi^0$ ($|cos\theta^*| < 0.8$) n is obtained to be $10.5 \pm 1.2 \pm 0.5$. The n values are summarized in Table 2 together with those from other processes. The ratio $d\sigma(\eta\pi^0)/d\sigma(\pi^0\pi^0)$ is consistent with leading-order calculation of 0.46 if f_η/f_{π^0} is 1.

3. $X(3915)$ and $X(4350)$

We search for charmoniumlike states in the $\gamma\gamma \to \omega J/\psi$ [19] and $\phi J/\psi$ [20] processes. In the $\omega J/\psi$ invariant mass spectrum, a peak is observed near $\omega J/\psi$ threshold (Figure 2). Measured values for the peak (Table 3) are consistent with those of $Y(3940)$ [21] observed in the $\omega J/\psi$ final state, and consistent with $Z(3930)$ seen in $\gamma\gamma \to D\bar{D}$ [7], which is likely to be χ'_{c2}.

Motivated by a resonance-like peak named $Y(4140)$ found in $\phi J/\psi$ invariant mass spectrum by CDF [22], the $\gamma\gamma \to \phi J/\psi$ process is studied. No $Y(4140)$ signal is observed. This disfavors the scenario in which the $Y(4140)$ is a $D_s^{*+}D_s^{*-}$ molecule with $J^{PC} = 0^{++}$ or 2^{++}. Instead, evidence of an unexpected new narrow structure, $X(4350)$ is found (Figure 2 and Table 3). This

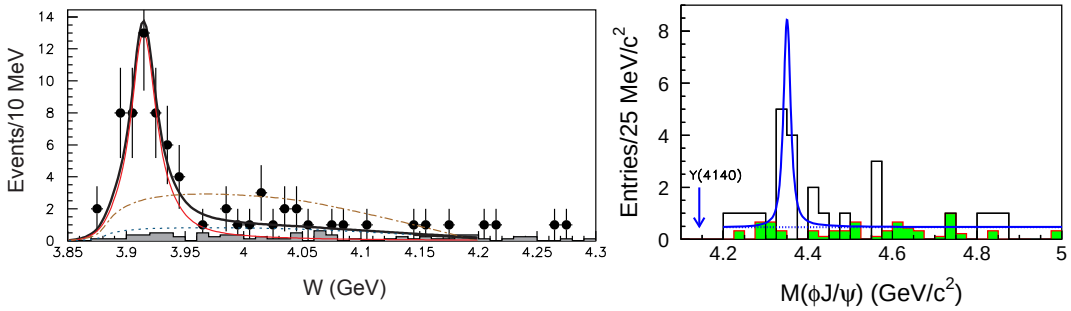

Figure 2. Left: $X(3915)$ in $\gamma\gamma \to \omega J/\psi$ invariant mass distribution (dots with error bars) with estimated background (shaded histgram) with curves from fit results [19]. Right: $Y(4350)$ in $\phi J/\psi$ invariant mass distribution (open histogram) with estimated background (shaded histogram). The solid curve is the best fit and the dashed curve is the background [20].

is interpreted as a $c\bar{c}s\bar{s}$ tetraquark state with $J^{PC} = 2^{++}$ [23] or a $D_s^{*+}D_{s0}^{*-}$ molecular state [24] or an excited P-wave charmonium state, χ_{c2}'' [25].

4. Conclusion

We have measured the diffential cross sections of the two-photon production of pure neutral final states, $\gamma\gamma \to \pi^0\pi^0$ and $\eta\pi^0$, using a high-statistics data sample collected with the Belle detector at the KEKB accelerator. We perform the partial wave analyses to study the light resonances. In the higher energy region, QCD predictions are compared to the data. The power-law dependence of the total cross section, $\sigma \propto W^{-n}$ and their ratios are presented.

We have observed a charmoniumlike peak $X(3915)$ in $\omega J/\psi$ invariant mass distribution and found evidence of a resonance-like structure $X(4350)$ in $\phi J/\psi$ mass spectrum, but no signal is observed at energy of $Y(4140)$.

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